Digital Modem for Two-Way Satellite Time Transfer

ESA NAVISP Element 2 programme (EL2-063)

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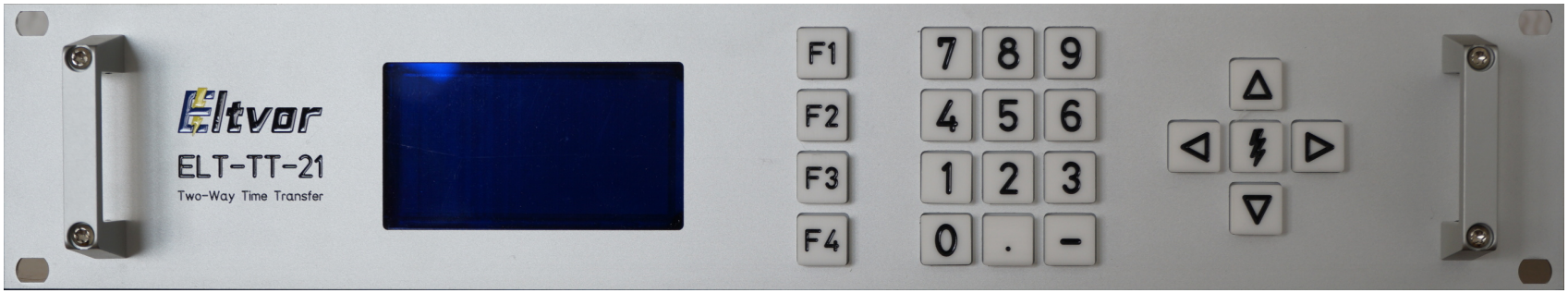
Digital modem for TWSTFT

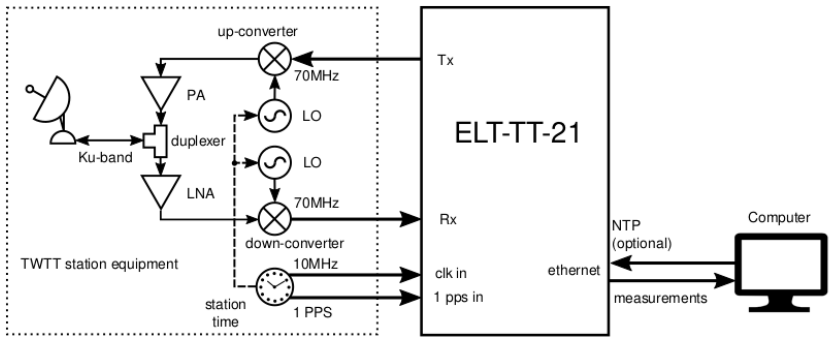
- TWSTFT = Two-Way Satellite Time and Frequency Transfer



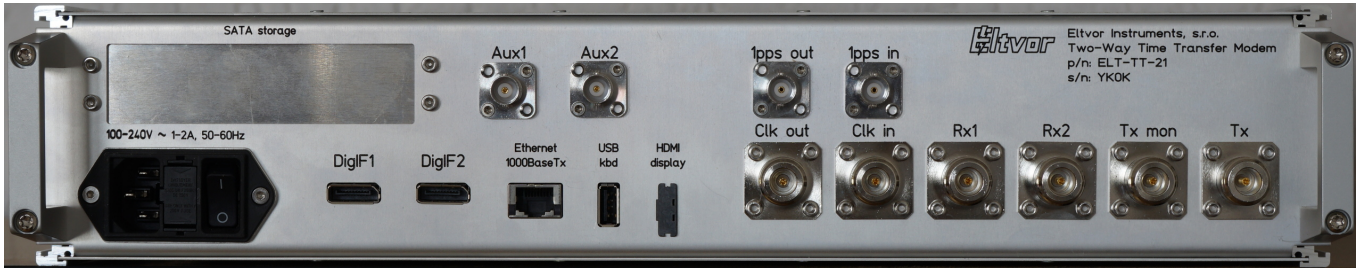
- Eltvor ELT-TT-21: digital, real-time, independent TWSTFT modem
- Ground station modem
  - operates over a bent-pipe transponder (typically GEO)
  - interfaces to local station's clock

TWSTFT – Overview

- $\geq$ 2 G/S over a transparent transponder
- Compares distant clocks
- Two-Way transmission decouples time vs. path length (range)
  - No need for elaborate modelling of orbits and atmosphere
- (Usually) positive SNR
- Independent of GNSSes
  - but may serve to the GNSS – used in BeiDou, IRNSS, QZSS



ELT-TT-21 Features



- 1×Tx & 2×Rx
  - may work over 1 or 2 satellites (terminals) simultaneously
- 8× HW Rx correlator
  - 8 PN-codes tracked simultaneously
  - >8 channels: chained modems (DigIF), or time mux
- Tx/Rx IF: 70MHz (BW=40MHz)
  - option: 140MHz (BW=80MHz)
- Clk in (10MHz) + 1pps in for local time reference
- Clk out (10MHz) + 1pps out for master/slave mode – clock re-generation

Design

- Rx: Digital, HW correlators
  - FPGA-based real-time processing
  - code & carrier tracking
- Tx: digitally-defined Tx filter mask
- chiprates: 1M, 2M5, 5M, 10M, 20M (chips/s)
  - waveform: BPSK, extensible with BOC (tested)
- 1s-frame synchronisation & data
  - pseudo-random ELT250 data modulation
    - for improved systematic error reduction
  - mode backwards-compatible with SATRE[1] (8b/s, 250b/s)
    - no data extraction – frame sync only

[1] Legacy/competitor TWSTFT modem

Backward compatibility

Reverse engineering

- Current TWSTFT network relies on SATRE modems
- Not fully documented (by intent), partly in ITU R-REC-TF.1153-4
- ⇒ Reverse-engineering out of the air (TV dish) by Eltvor since 2015
- Tech Note written and made available to ESA

Reverse engineering of legacy TWSTFT signals — Technical Note

Goal

At the beginning of our work towards the independent TWSTFT implementation in 2015, we always wished our conception to be backwards-compatible with the existing TWSTFT network to allow interoperation, possible replacement of existing equipment etc.

Some of the TWSTFT signal characteristics were documented in public sources, such as ITU R-REC-TF.1153-4, SATRE modem datasheet, or BIPM TWSTFT Calibration Guidelines for UTC Time Links. Nevertheless, there were still several key parameters left undocumented, namely:

- PN codes in use, and in general, code family;
- code length (period);
- disambiguation of code period modulus (1-second marker);
- data modulation.

An easy possibility to find out would be to sample the existing SATRE modem's Tx IF port using SDR or oscilloscope and read the code parameters directly. For several reasons — fun factor of the technical challenge and avoidance of physical contact with competitor's modem — we decided to try inferring the unknown code parameters out of the air interface.

Method

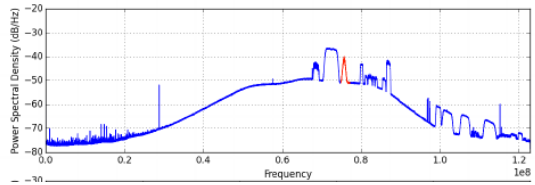
Space and ground segment

In order to acquire the unknown singals, we first had to identify the satellite and transponder parameters. This was fortunately mentioned in BIPM Calibration Guidelines: the satellite with European downlink was found to be Telstar 11N, at the time of cracking with 2.25MHz channel allocated, and nominal chiprate 1Mchip/s. Another helpful resource was the Telstar 11N User Manual.

We took an 80cm Ku-band TV-grade dish with a DRO (!) based LNB (yes, it worked). The L-band IF was frequency-converted to VHF IF, and sampled directly by an ADC and FPGA setup, which later evolved into ELT-TT-21.

Even with the 80cm dish, the TWSTFT signals were visible on a spectrum analyser (PSD) plot with a positive SNR of several dB (around +6dB at the time). To our initial surprise, the signals were missing for every other hour, sometimes replaced by CW signals. This has been confirmed by a TWSTFT community member as correct: odd UTC hour is designated for experiments.

Once the signals were identified, the raw IF signal was sampled and stored, with a duration slightly below 2s. There was a large carrier center uncertainty due to LNB DRO offset, so the signal was coarsely centered around the "hill top".



Lab test: loopback

- Tx $\rightarrow$ Rx1 loopback
- code phase jitter, duration 600s, $\tau = 1s$:

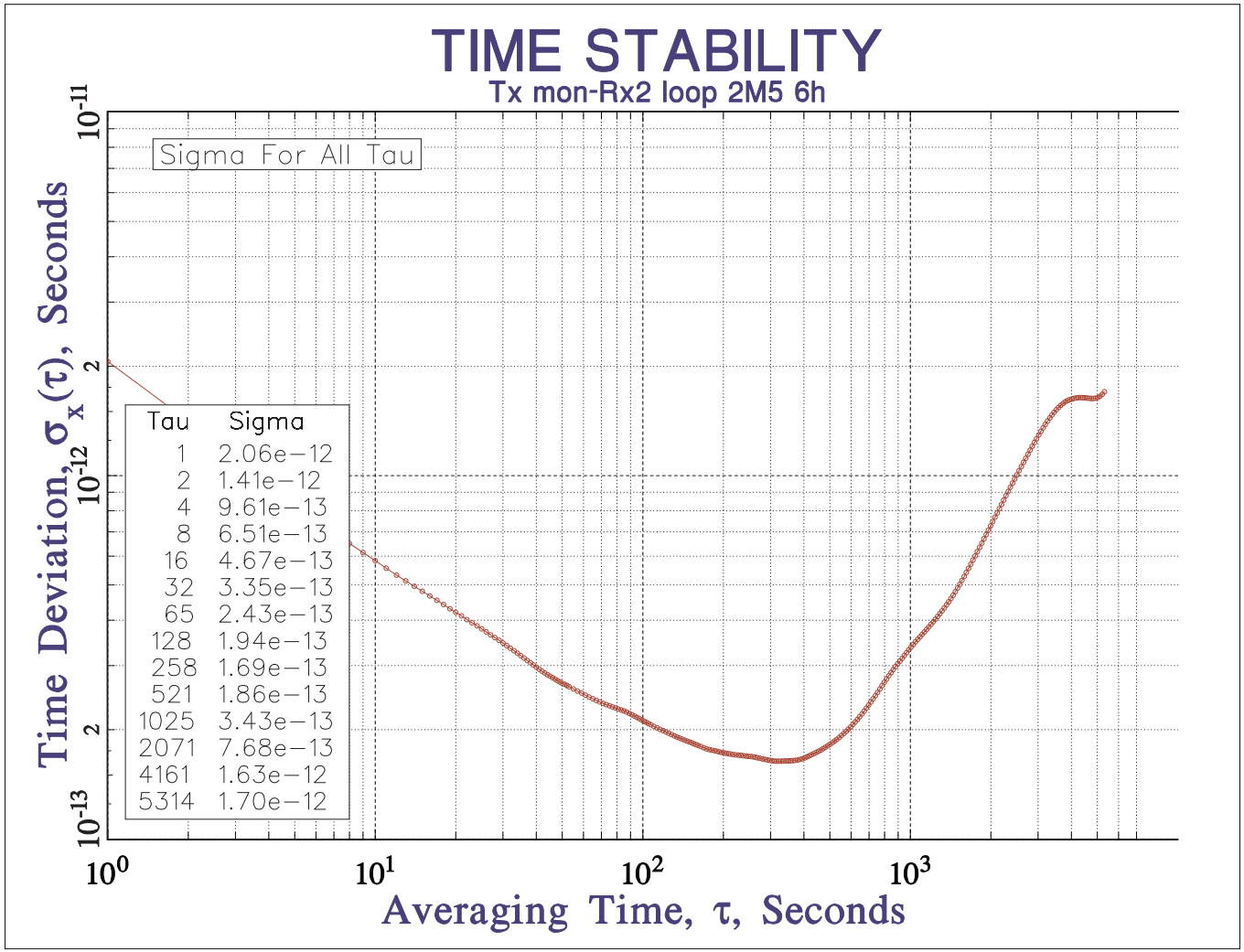
chiprate	legacy mode	ELT250 mode
1M	2.6	1.8
2M5	5.0	0.5
5M	8.5	0.3
10M	5.6	(0.1)
20M	5.3	(0.1)

Table: Jitter $\sigma(\tau = 1s)[\mathrm{ps}_{RMS}]$ of Tx–Rx1 loopback at various chiprates

- $\geq$10M: limited by systematics $\approx \pm 0.2\,\mathrm{ps}$

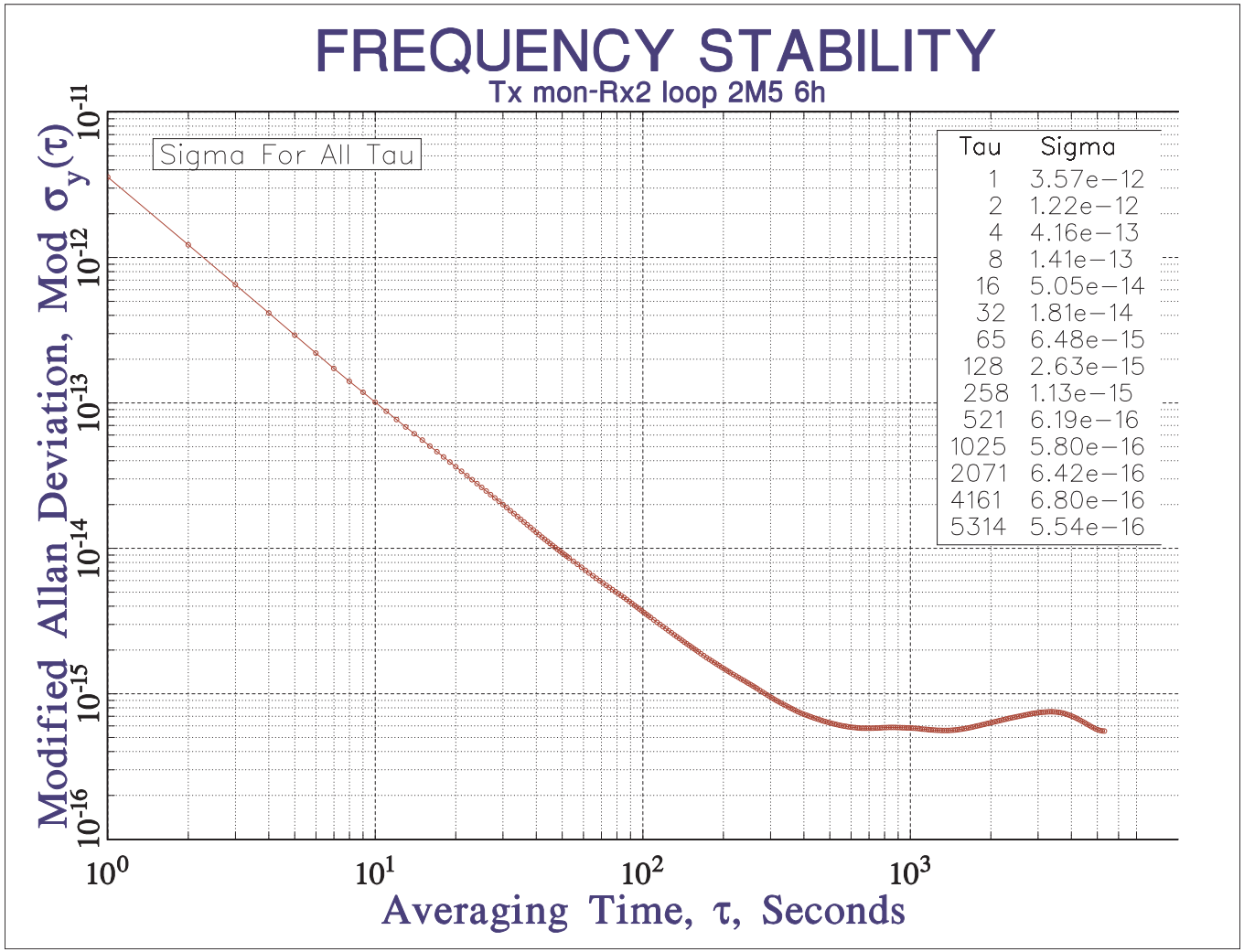
Lab test: loopback – Tdev

- 2.5Mchip/s, duration 6h, room w/o temperature control



Lab test: loopback – Mdev

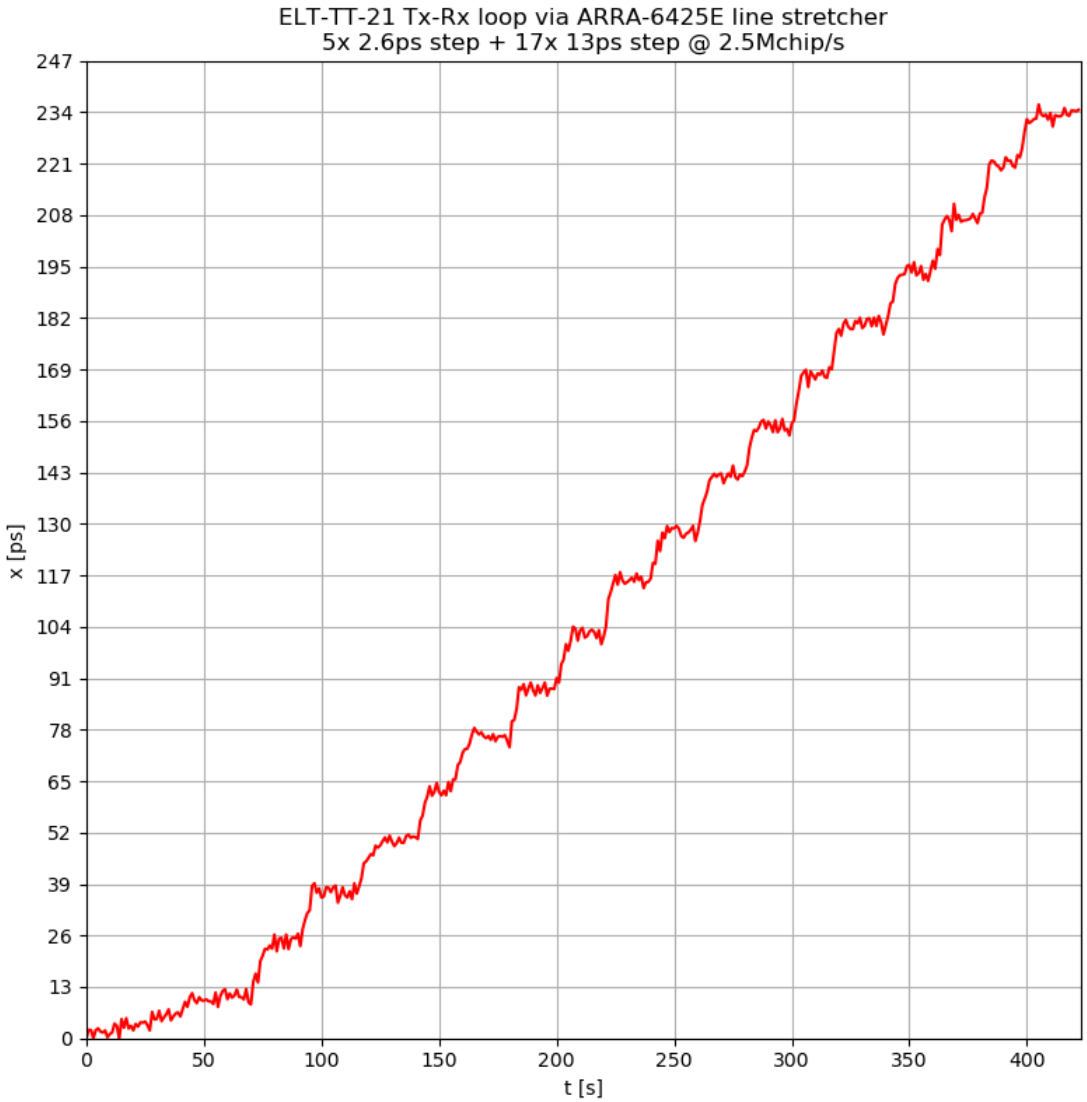
- 2.5Mchip/s, duration 6h, room w/o temperature control



Lab test: delay line

- Tx → mechanical delay line stretcher → Rx1
- 2.5Mchip/s, 4 × 2.6ps + 17 × 13ps steps (manual)

Lab test: delay line – results



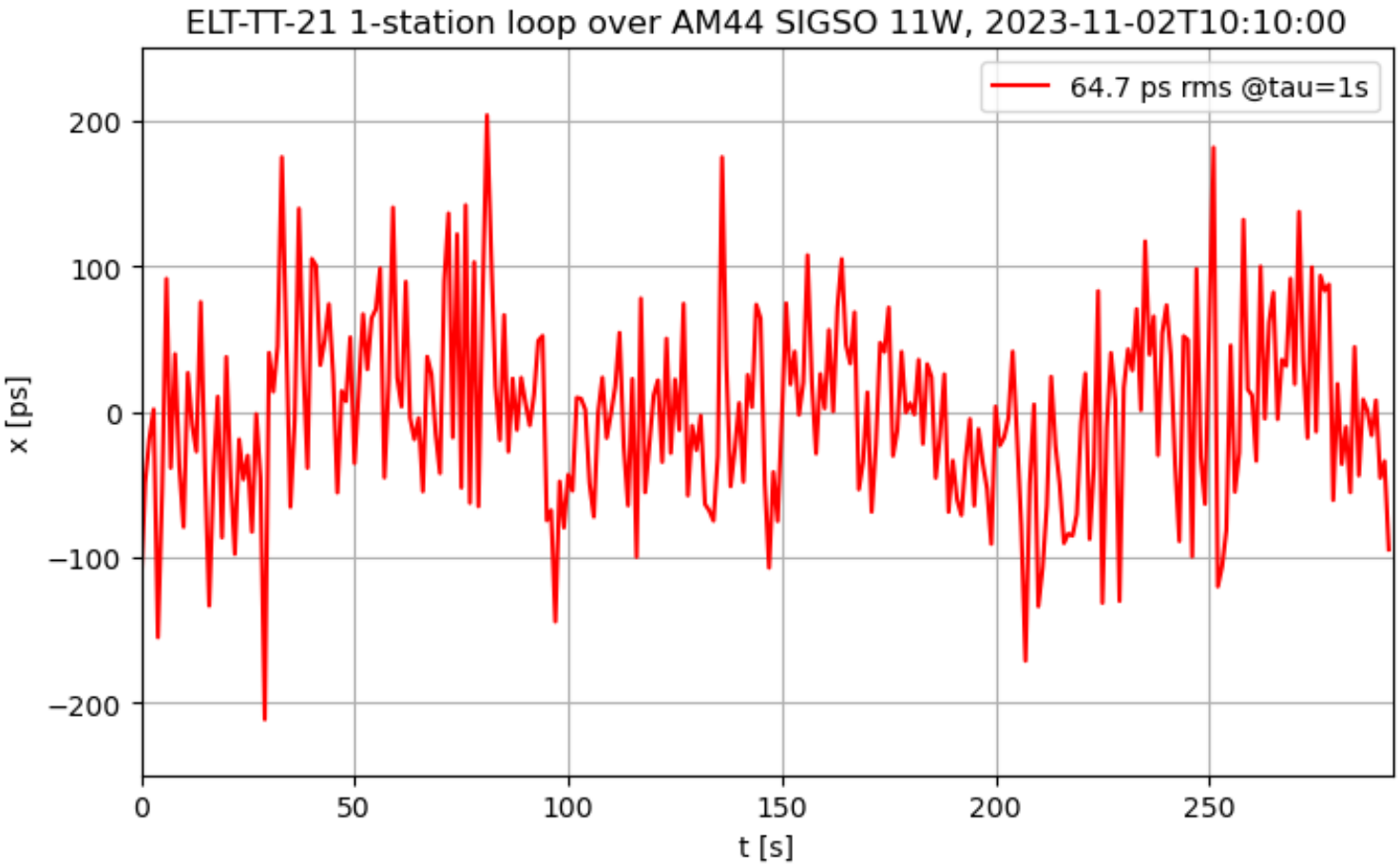
GEO (SIGSO[2]) 1-station ranging

- G/S: Pecný, 2.4m Ku-band terminal equipped with Eltvor RF signal path
  - antenna, ground works, cabling – all done/procured by Eltvor; passive (Rx-only) mode running for 2 years
- S/C: Express AM-44 (11W)

[2]Slightly Inclined Geo-Synchronous Orbit – a retired GEO sat

GEO (SIGSO) 1-station ranging – results

- 2.5Mchip/s, duration 300s, 4.5MHz BW $\rightarrow$ $\sigma(\tau = 1s) = 64.7\text{ps}_{RMS}$

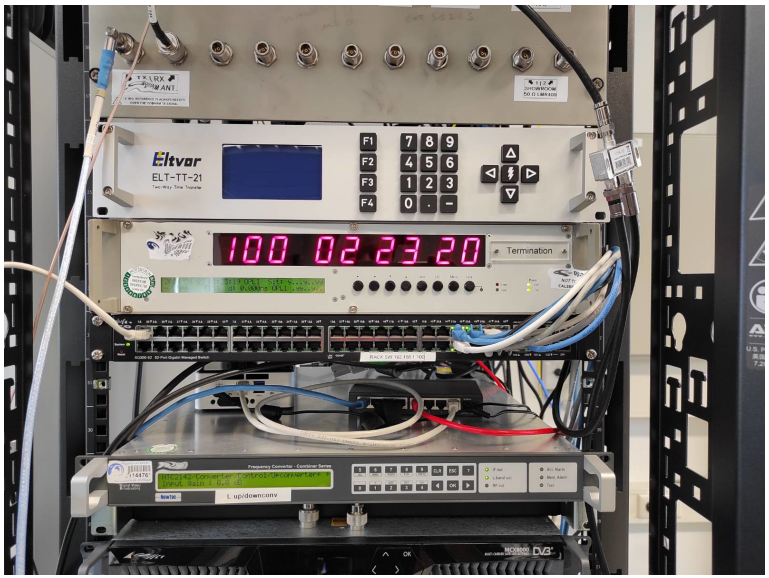


Two-Way GEO (SIGSO) test

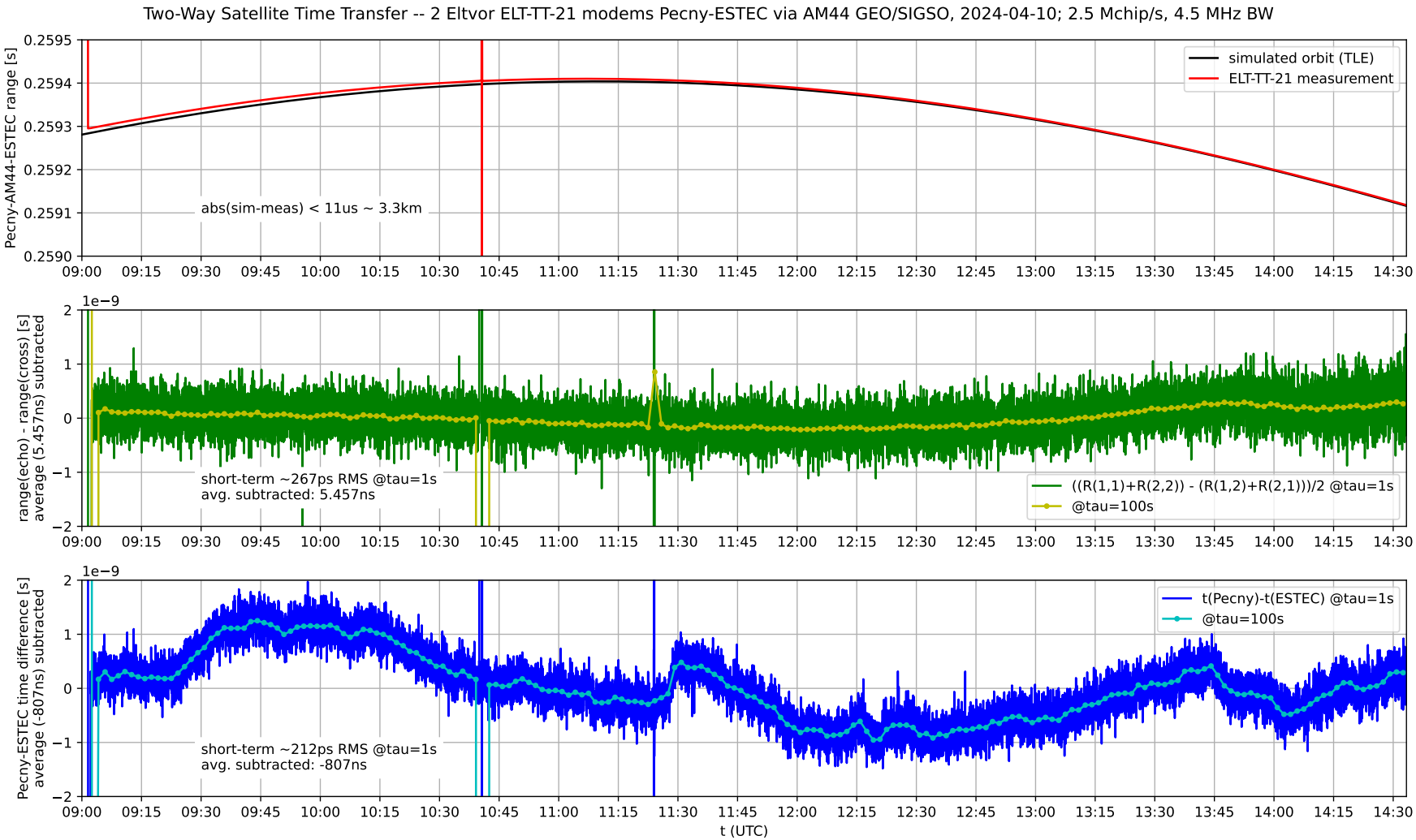
- Pecný $\leftrightarrow$ AM-44 $\leftrightarrow$ ESTEC
  - 780 km baseline
- 2$\times$ ELT-TT-21 installed at both sites

Pecný:

ESTEC:



Two-Way GEO (SIGSO) test – results



Two-Way GEO (SIGSO) test – legend

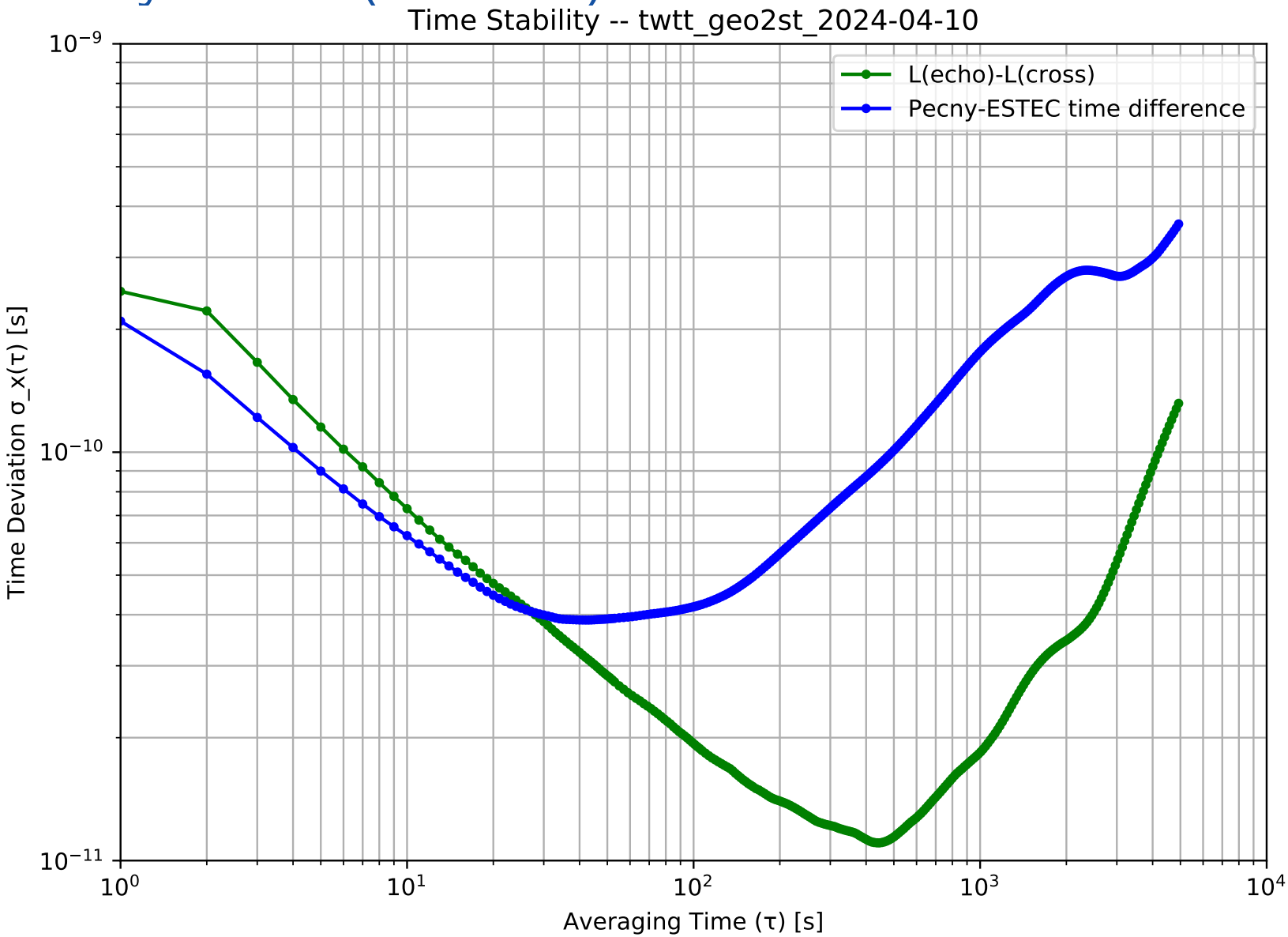
- ideal vacuum assumed, no iono, no Sagnac corrections

1. Pecný–AM-44–ESTEC range [s]: measured delay vs. TLE-calculated
2. difference between 2 range measurements:
   - $L_1 = 1/2$[echo(Pecný) + echo(ESTEC)]
   - $L_2 = 1/2$[delay(Pecný,ESTEC) + delay(ESTEC,Pecný)]
3. UTC(Pecný)-UTC(ESTEC): measured TWSTFT vs. assumed equal

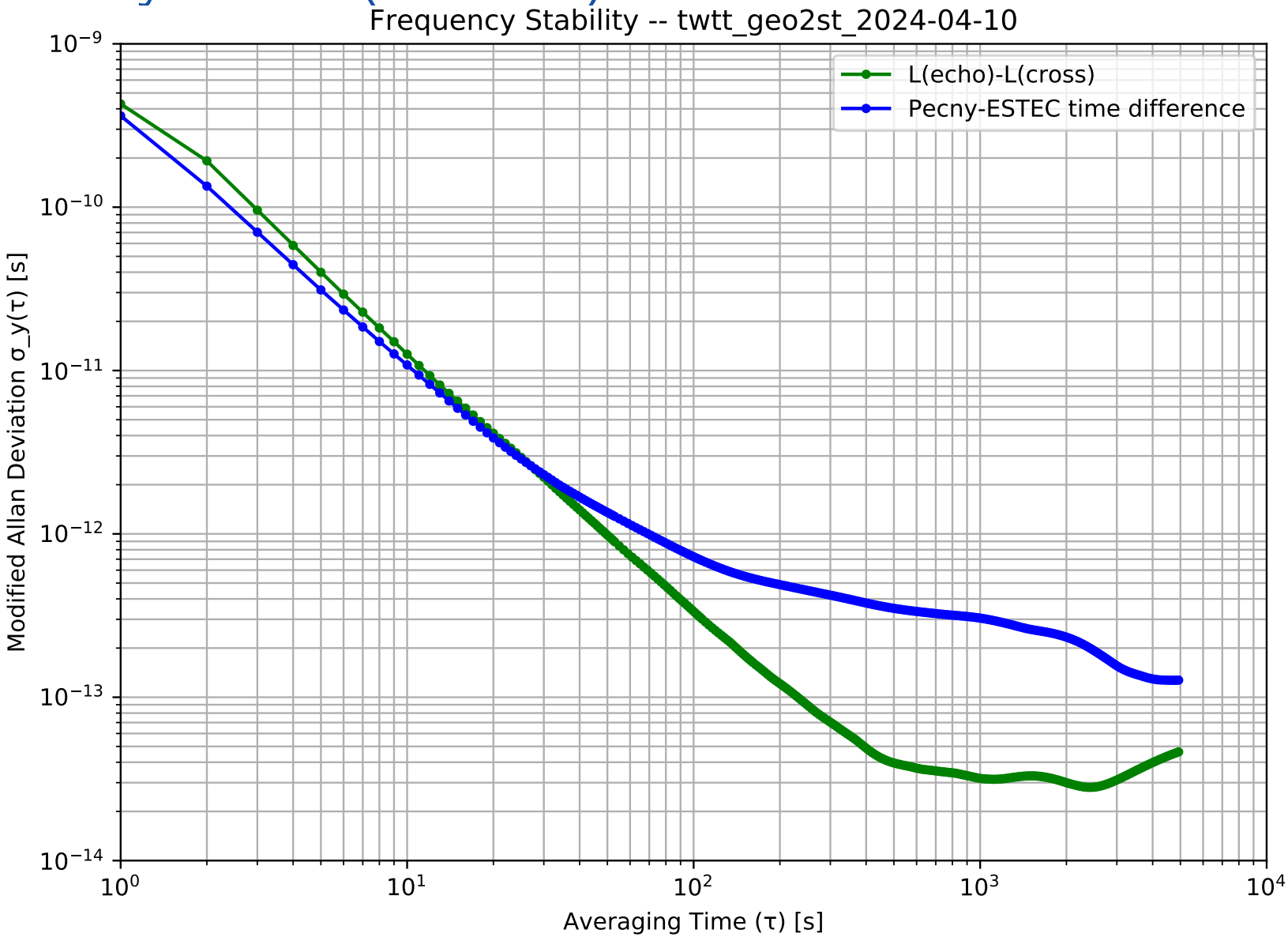
Two-Way GEO (SIGSO) test – comments

- 2 glitches due to transponder interference
  - 1st glitch: ESTEC operator shut down Tx, Rx'es re-locked
  - 2nd glitch: Tx remained on – Rx'es locked, increased jitter RMS
  - ... both gracefully recovered
- due to SIGSO:
  - 90km pk-pk range drift, apogee, both high&low Doppler, amplitude fading
- time difference vs. GNSS-referenced UTC: $\pm$1ns
  - reference time diff between UTC(ESTEC) & UTC(TP) itself varying $\approx \pm$1ns $\Rightarrow$ inconclusive
  - $\Rightarrow$ 2-terminals, 2-modems, 1-site common-clock experiment most wanted

Two-Way GEO (SIGSO) test – Tdev



Two-Way GEO (SIGSO) test – Mdev



Wrap-up of the experiments

- ELT-TT-21 modem presented
- Lab results
  - Tx-Rx IF loopback: 0.5ps_{RMS} @2M5, ± 0.2ps @20M
  - Mdev 6×10^{-16} @$\tau > 500$s
  - 13ps stepper
- GEO (SIGSO) results
  - 1 station, short term, 64.7ps_{RMS} @2M5 (4.5MHz)
  - 2 stations: Mdev 3×10^{-13} @$\tau > 1000s$, likely limited by local UTC variations

Outlook – experiments and development

- Proposed experiments[3]:
  - Common-clock over GEO
  - Two fiber-linked stations over GEO
- Proposed upgrade:
  - GNUradio interface over 1000BaseTx to support community, SDR-based TWSTFT using ELT-TT-21 as a front-end
- Current commercial interest:
  - Resilient/regional PNT
    - GPS/GNSS-independend timing
  - National institutes of metrology new to TWSTFT
  - Upgrade of existing national institutes of metrology TWSTFT

[3]Multi-lateral negotiations underway, especially to secure GEO transponder access for long-term

Common-clock experiment

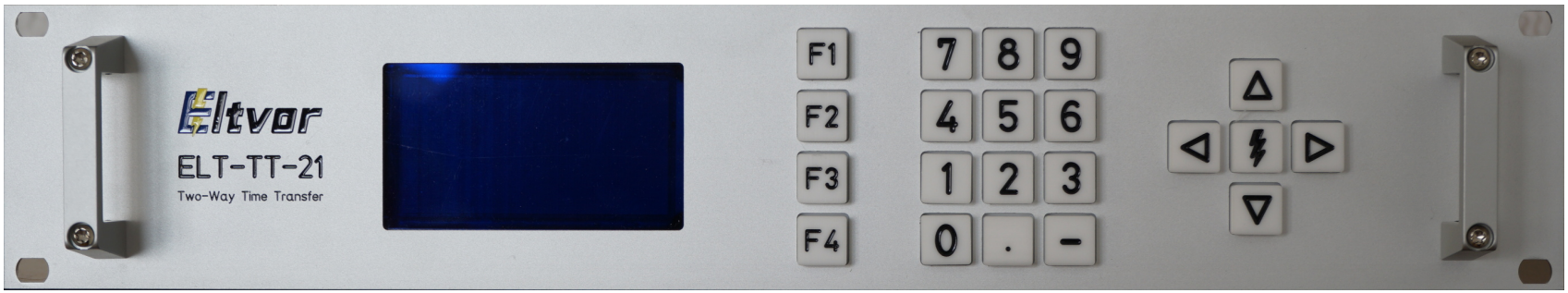
- Two Ku-band terminals installed at one site
  - new, 2.4m terminals
  - to be installed at Eltvor site in Tábor, CZ
- Two modems, common clock
- GEO transponder to be used under assessment

Two fiber-linked stations experiment

- 1st station: ESA ESTEC
  - one dedicated 2.4m Ku-band terminal
- 2nd station: VSL NL
  - preferably a shared terminal with VSL's TWSTFT
- pre-existing fiber link VSL–ESTEC
- GEO transponder to be used under assessment

The End

* Available for order *



Thank you for your attention.